

Applying solenoids: Flying blind is not recommended

SOLENOIDS—ESPECIALLY IN APPLICATIONS THAT REQUIRE THEM TO RAPIDLY ENERGIZE AND DE-ENERGIZE—REQUIRE AN UNDERSTANDING OF THEIR OPERATIONAL SUBTLETIES AND YOUR CONTROL-CIRCUIT OPTIONS.

Driving a dc solenoid as a control-loop element can be difficult, even though a solenoid is a simple device. Many applications require the solenoid to engage several times a second, especially if the control loop is regulating a fluid's rate of flow from a valve.

The use of digital logic can tempt you to try to drive a solenoid as though it were a relay—from a logic-device output via a transistor—but, in some applications, this approach is a mistake. Such power sources as batteries need voltage head room to supply current to the solenoid while powering the rest of the system. Even if the solenoid's average power is low, the peak current drawn from the battery, especially near the end of its life, can create a brownout condition. Conversely, if the voltage is high, the current through the solenoid coil can heat the device to the point of malfunction.

Some of the problems you might experience from this type of circuit are dropout conditions, in which the solenoid fails to engage, and long turn-on and turn-off times. If the solenoid is in a control loop, the loop could become unstable and destroy the solenoid. Few things smell worse than burning magnet wire and varnish. If it must be part of a control loop, a solenoid nearly always requires a carefully chosen method of active-current control.

As an electrical load, a solenoid behaves as an air-core inductor. In essence, a solenoid consists of magnet wire wrapped around a plastic, ceramic, or brass bobbin with a ferrous case (Figure 1). The case contains the magnetic field that you generate when you drive current through the solenoid coil. A plunger made of ferrous material completes the magnetic path. The bobbin can also serve as a bearing for the plunger. As the air gap between the plunger and the case decreases, the magnetic field gets stronger, and the force that the plunger exerts on the load increases. Once you've completely seated the plunger in the bobbin, its top and bottom close the air gap. The magnetic field flows through the top of the plunger and out the bottom. At first, the solenoid's inductance is high because of the large air gap. Because a magnetic field flows through iron more easily than it flows through air, the coil needs the most current initially to generate a field strong enough to actuate the plunger. The required initial current is the turn-on, or pull-in, current. Once the magnetic field is shorted through the case and the plunger, a smaller current—the hold current—can keep the solenoid closed, because the ferrous case and plunger carry the magnetic field.

An electromechanical relay is a reactive device you use to

actuate a switch. Electronically, relays and solenoids are similar, because you can treat both as inductors, but the similarity ends there. A solenoid resembles a motor more than it does a relay. You use solenoids, like motors, to convert energy from one form to another—usually electrical power to mechanical motion. Solenoid motion can be rotational or linear but is typically unidirectional with a return spring bringing the plunger or arm back from the actuated position. Some solenoids operate bidirectionally, but they require two drive circuits. You must limit the on-time of most solenoids because of damage that can occur from heating of the wire. One way to limit heating is to reduce the voltage across the coil after you've actuated the solenoid and closed the air gap.

Figure 2 shows a solenoid as the control element in a feedback loop. The controller sends commands to actuate the solenoid, which controls a process. In this example, the solenoid gates fuel a thruster valve. Solenoids open the valves; springs close them. The requirements for the solenoids specify opening and closing times, maximum and minimum on-times, duty cycle, and repeatability. The example reviews two control methods: open and closed loop. At first glance, it was tempting to use a transistor array to drive the solenoid from a logic device in an open voltage loop. If you had a stable power source for the drive, an open-loop voltage-switching transistor array might work. A stable power source is not the only factor

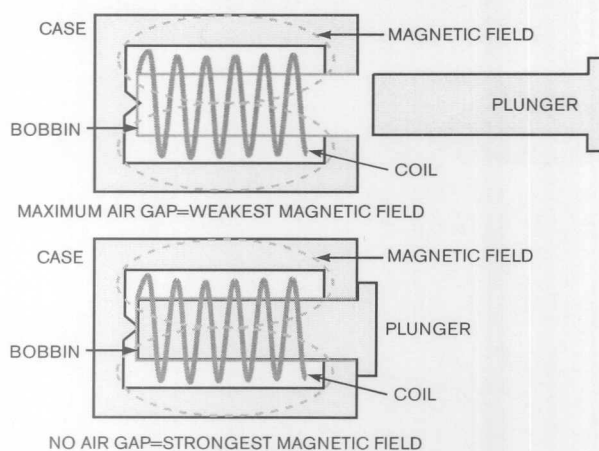


Figure 1 In essence, a solenoid consists of magnet wire wrapped around a plastic, ceramic, or brass bobbin with a ferrous case.

that determines the control method, however. Variability in the solenoid's operation can cause problems. On- and off-times become dependent on voltage changes and on the solenoid's dc resistance. In this example, the power source is a thermal battery that exhibits its voltage decay as great as 10V. In the open-loop configuration, you must specify the solenoid's operation at the minimum voltage level—when the battery nears the end of its functional capacity. A closed current loop requires more components, and the loop's behavior must not interfere with the process controller's performance. Before you can select a control method, you must thoroughly understand the solenoid's load characteristics and the operational parameters of the process under control.

You can treat solenoids in a driven load as inductors. However, you must consider some solenoid characteristics when you size your power source and drive circuits. Solenoids are built not for a specific inductance value, but to achieve torque. As a solenoid actuates, its inductance changes. So, during operation, the electrical load behaves as if it were a variable inductor. The amount of torque that the solenoid can generate depends on the strength of the magnetic field. Field strength relates to the current in the coil and the number of turns of wire on the bobbin. If you need more torque, you need either more current or more turns of wire. The coil inductance and the dc resistance of the wire wound around the bobbin limit the solenoid current. The solenoids in this application were small but had an initial inductance of 3.3 mH and a dc resistance of 15Ω. To get the torque required to overcome the spring and open the valve, the driver had to supply 2.2A for 5 msec at pull-in and 0.75A to hold for as long as 2 sec. After this current-versus-time profile, the solenoid had to be able to respond again within 20 msec. According to Ohm's Law, the driver had to supply at least 33V to the coil during turn-on and 11.25V to hold.

Initially, it appeared that voltage control might be appropriate, but there were some other issues to consider. As current flows through the coil, the wire becomes warmer and its resistance increases—an effect known as I^2 loss. The gauge of the wire in the coil determines how much self-heating occurs. The thermal mass of the solenoid helps to dissipate the heat, but the turn-off time of only 20 msec does not allow for much dissipation. These solenoids were wrapped with approximately 435 in. of #36 AWG magnet wire. The following equation predicts the coil's self-heating as an algebraic adaptation of the fusing-current equation: $T = T_A + 10^{(33S(I/A)^2 - 1) \times (234 + T_A)}$, where S is the application time in seconds, T is the end temperature of the wire after S seconds, A is the area in square mils of the conductor, I is the application current, and T_A is the ambient temperature (Reference 1). The equation for calculating the resistance of the wire is: $R_t = R_{20} \times [1 + a_{20} \times (t - 20)]$, where R_{20} is the resistance at 20°C, a_{20} is the temperature coef-

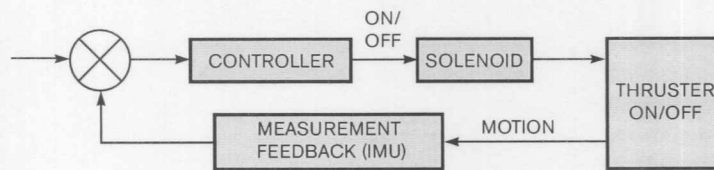


Figure 2 A solenoid is part of the feedforward path of this feedback-control system, which controls the delivery of fuel to a thruster valve.

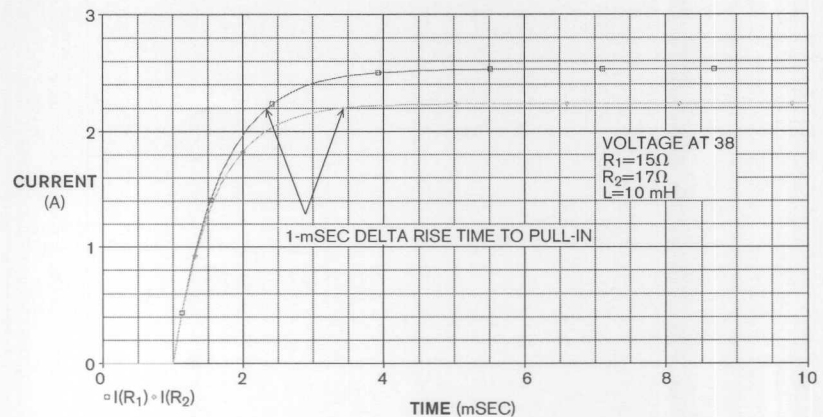


Figure 3 Thermally induced changes in dc resistance affect a solenoid's pull-in and release times. As the dc resistance changes, the charging-time constant also changes. This PSPICE plot shows the time-constant variation.

ficient of resistance for copper at 20°C=0.00393, and t is the end temperature (Reference 2).

Using these equations together and the earlier described current-versus-time profile, the coil resistance after the first cycle is 17.3Ω. The voltage required to achieve pull-in during the next pulse increases to 38.1V. The hold voltage increases to 13V. The increase in temperature does not include any soak back from the thruster itself, and normal variations in dc resistance are not associated with the coil winding. After a few more actuations, the solenoid heats up so much that it can no longer achieve the turn-on current. The result is that the fuel going to the thruster either is not properly regulated or simply fails to reach the thruster.

The change in dc resistance also affects the solenoid's pull-in and release times. As the dc resistance changes, the charging-time constant also changes. Figure 3, a PSPICE plot, shows the temperature-induced time-constant variation. The example uses a power supply of 38V so that both inductors could reach a current of 2.2A. The plot clearly shows a 1-msec difference in the time to reach the turn-on current. The solenoid does not actuate until the device has reached the turn-on current.

A BETTER CHOICE

An inductor's charging-time constant is the inductance divided by the resistance; for a solenoid, the relationship becomes the inductance divided by the dc resistance. In a sole-

noid, the longer it takes to achieve the turn-on current, the hotter the wire gets, and the hotter the wire, the larger the dc resistance. Controlling the voltage across the solenoid does not help. Changes in dc resistance over time affect the solenoid's actuation time. Because an inductor is a current-dependent device—that is, the voltage across it is proportional to the first derivative of the current through it—controlling the current in the coil is the better choice. In this application, all of the variables associated with the solenoid's behavior make it challenging if not impossible to achieve consistent operation in an open loop. Closed-loop control is obviously necessary.

Controlling the voltage makes no sense. Because an inductor is a current-dependent device, you must control the current in the inductor. Doing so can ensure reliable operation. Update the control loop of **Figure 2** to add a current loop in the solenoid-control-element box (**Figure 4**). The elements of the current loop are the solenoid coil, the PWM (pulse-width modulator), and the feedback amplifier. The controller is an on/off-type element that may supply fuel to the thruster. The current loop is inside or nested in the fuel-command-control loop. The process loop establishes the requirements for the current loop. A complete understanding of the process loop's functional requirements is critical to properly designing the current loop. This example uses a 50-Hz process-control loop. That is, update commands from the controller to the solenoid-control element's summing junction occur every 20 msec. To fully meet the thruster demand before the controller's next command, the solenoid-

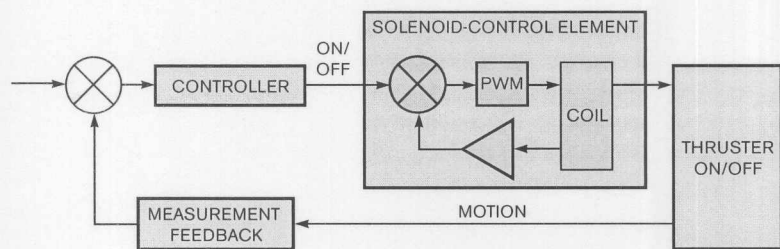


Figure 4 The elements of the current loop are the solenoid coil, the PWM (pulse-width modulator), and the feedback amplifier. The controller is an on/off-type element, which may supply fuel to the thruster. The current loop is inside or nested in the fuel-command-control loop.

control element must respond to the commands in much less time than the reciprocal of the update rate. The current loop's frequency response must be much faster than that of the process loop; a bandwidth of at least five to 10 times that of the outer loop is a good rule of thumb, because it ensures that the solenoid loop does not create instability in the outer loop. Therefore, a bandwidth of 1 kHz should work.

SYNCHRONIZE WITH THE SYSTEM CLOCK

Figure 5 shows the solenoid-control-element and the control-signal-timing relationships. The PWM-clock frequency must be high enough to establish the resolution of the drive current. Fortunately, the solenoid is a binary device; it is either on (2.2A) or off (0A). The circuit's two control points are turn-on (2.2A) and hold (0.75A). If the solenoid is part of

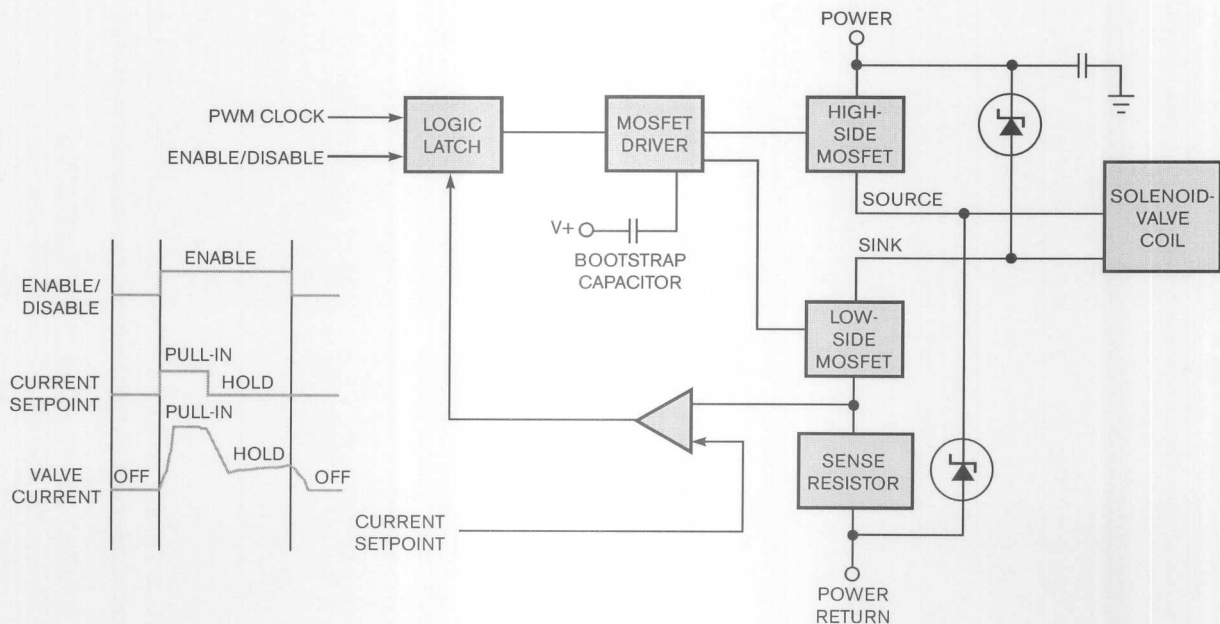


Figure 5 In the solenoid-control-element and control-signal relationships, the PWM-clock frequency must be high enough to establish the resolution of the drive current.

a larger system with sensitive electronics nearby, it might be best to synchronize the PWM clock with the system clock. To pick the right PWM frequency, you must completely understand the system's noise susceptibility.

The impedance of the solenoid helps to determine how much capacitance you need to shape the load at the PWM frequency. The FET drivers are other considerations; the higher the PWM frequency, the greater the switching loss. This example uses a PWM frequency of 125 kHz with a duty cycle of 90%. Rather than trying to control a current of 0A, the enable/disable input allows the current-setpoint command to drive the solenoid and turn off or disable the solenoid. Turning off the PWM frequency disables the drive circuitry. The enable/disable input is also a safety feature that ensures that a valve is active only when necessary.

The current setpoint can be logic high or low; in this example, 5V at the current setpoint commands the pull-in current, and 0V commands the hold current. The power for driving the solenoid coil comes from a pair of 28V (nominal) thermal batteries that produce a total of 56V. The terminal voltage of the 28V batteries drifts from 32V at initiation to 24V at the end of life. Thus, the supply-voltage range is 48 to 64V.

BASIC OPERATION

Basic operation consists of applying a 90%-duty-cycle PWM clock to the high- and low-side MOSFETs. Once the current in the inductor reaches the pull-in current, the comparator latches out the PWM signal. When the current-setpoint command goes low, the comparator latches in the PWM signal until the coil current drops below the hold current.

MOSFETs with very low drain-to-source resistance act as the high- and low-side drivers. These devices allow you to use the entire battery voltage, minus the drop across the FET, to build the coil current as fast as possible. The PWM clock's 90% duty cycle makes the effective battery voltage 50.4V. You must size the MOSFETs to the proper solenoid turn-on current. You should also derate the MOSFET to create some margin in the design. Typically, a MOSFET with a drain current of at least two times the pull-in current is a good starting point. You must also derate the MOSFET for drain-to-source voltage. A factor of two is usually acceptable. Derating requirements depend on the customer. If you are designing a product for which safety is not critical, the derating guidelines are less stringent.

Conversely, safety-critical systems require more stringent guidelines. You are responsible for understanding all of the design requirements, not just the functional ones. N-channel enhancement-mode MOSFETs are the best choices. You can use the same part number for both devices. You must bootstrap the high-side FET to achieve the proper gate-to-source voltage to turn on. Bootstrapping is available on most MOSFET-drive ICs. The IC's data sheet provides the formula for calculating the bootstrap-capacitor value. The load capacitor is in parallel with the power. The capacitor provides the initial current surge into the inductor and filters the switch noise in the system. You must size the capacitor to the load—that is, to the inductor. The capacitor compensates for the current lag and provides the surge current for the solenoid. Sizing the capacitor to lead the current and balancing the power in the load are not as important as providing enough current during the

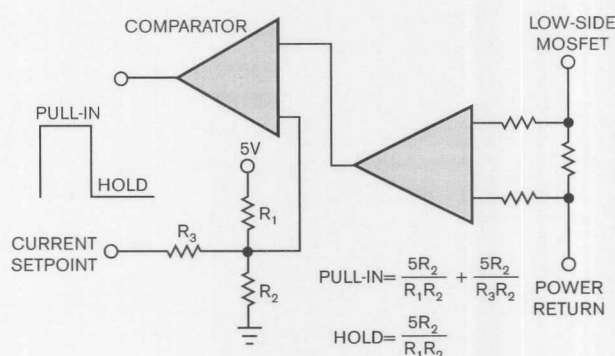


Figure 6 The current-sense resistor and the comparator close the loop for the current-control circuit. The comparator compares the voltage from the sense resistor with the voltage from the current-setpoint command. The current-setpoint command goes through a voltage divider to set the solenoid's current value.

initial turn-on, especially when the power source is some distance away and not right next to the drive circuits. A ceramic capacitor works best because of a low ESR (equivalent series resistance). This application requires a voltage drop of no more than 2V at the power source during PWM switching. The capacitor must be able to supply current to the inductor for 90% of the PWM duty cycle, or 7.2 μsec . The equation for determining the capacitor is: $dV = I \times (dt/C) + I \times R$, which you solve for C. $C = I \times dt / (dV - IR)$, where dV is the change in voltage of 2V; I is the pull-in current of 2.2A; and R is the ESR of the ceramic capacitor, 100 m Ω , at the PWM frequency. Solving the equation, $C = 2.2A \times 7.2 \mu\text{sec} / (2V - (0.1\Omega \times 2.2A))$.

The capacitance must be at least 8.9 μF to keep the voltage at the load from dropping more than 2V during the turn-on current. You should round up the capacitor to the nearest commonly available value. The capacitor's voltage rating should be at least twice the supply voltage. Schottky diodes, such as 1N5804s, ensure that, when the inductor is turned off, the collapsing field's back EMF (electromotive force) short-circuits through the diodes, thus helping to turn off the solenoid as quickly as possible and reducing the amount of back EMF into the drive circuit.

The current-sense resistor and the comparator close the loop for the current-control circuit. The comparator compares the voltage from the sense resistor with the voltage from the current-setpoint command. The current-setpoint command goes through a voltage divider to set the solenoid's current value. Figure 6 shows the circuits required to close the current loop. The timing of the enable/disable and current-setpoint commands is critical. Enable/disable must go high at the same time the pull-in current goes high. After the device has achieved pull-in, the current setpoint goes low, providing the hold current to the solenoid. If you assert enable (high), current flows through the solenoid at the level that the current setpoint establishes.

SWITCHING NOISE

Because it is a switching system, the current-loop controller, by its nature, generates noise. The only way to keep the

noise from adversely affecting the rest of the system is to limit the paths from the switcher to any victim circuits that may be near. Experts have written volumes on the layout and routing of charge-coupled amplifiers (Reference 3). The amount of analysis depends on the noise susceptibility of the rest of the system. Some good ground rules are to keep the length of the traces from the MOSFETs to the capacitor and diodes as short as possible and to install resistors in series with the MOSFET gates to slow the switching transitions. Even a 0Ω resistor affords the opportunity to change the bandwidth at the MOSFET gate.

It is critical that the routing plane have a heavy ground plane no more than one dielectric layer away. The source and sink traces must be very wide, and it's best to route them on top of each other all the way to the connector. From the connector to the solenoid, use shielded, twisted-pair wire. When you compute the load resistance, remember to include the IR drop across the harness. Keeping the noise down in a circuit is about controlling current loops. Make sure to route the solenoid current using a low-impedance path of minimum length.

A solenoid is an inductive load. Inductors are current-controlled devices. The best method for driving a solenoid is a current-control loop. However, current-loop controllers take up more space in a design because of the increased component count. If there is enough board real estate, a current loop is

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the only way to go to get precise control over the solenoid. Incorporating as much of the loop into programmable logic is a way to reduce the number of components. The needs of the system dictate the type of control to use. The controller presented here is simple and consumes approximately 2 in.² of board area. More current requires more area. When precise solenoid operation is less important than board area, open-loop voltage control can work. **EDN**

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